NASA Technical Memorandum 102503

Spacelab Qualified Infrared Imager for Microgravity Science Experiments

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Prepared for the
Technical Symposium on Optical Engineering and Photonics in Aerospace Sensing
sponsored by the Society of Photo-Optical Instrumentation Engineers
Orlando, Florida, April 16–20, 1990

NASA

SPACELAB QUALIFIED INFRARED IMAGER FOR MICROGRAVITY SCIENCE APPLICATIONS

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ABSTRACT

The Lewis Research Center is developing, under contract, a Spacelab (manned module in the Space Shuttle payload bay) qualified infrared imager for non–contact surface temperature measurement in the Surface Tension Driven Convection Experiment, a microgravity fluid physics experiment. A versatile design philosophy was used in order to provide other experimenters with essentially an "off the shelf" Shuttle qualified instrument, eliminating the duplication of the rigorous development and flight qualification processes. An Inframetrics Model 600 Scanning Infrared Radiometer is being modified to satisfy both experimental and flight requirements, while maintaining the basic performance parameters of the commercial instrument. The modifications include an efficient, low power closed cycle cryogenic cooler to cool the detector, a ruggedized scanner mechanism, 8 bit A/D conversion, Mil–STD components (where possible), size and weight optimization, and the addition of a microprocessor to perform automatic gain control. Features such as detector spectral response, the addition of spectral filters, and target temperature ranges could easily be changed to make this instrument useful as both a qualitative and quantitative diagnostic tool for Spacelab microgravity experiments, in combustion and fluid physics.

1. INTRODUCTION

A non–contact surface temperature measurement system is being developed in response to the need for quantitative, full field characterization of the resulting surface temperature distributions during the Surface Tension Driven Convection Experiment (STDCE). The STDCE is a space flight experiment to study thermocapillary flows. The current STDCE schedule is to have flight hardware ready for shipment by April 1, 1991 for integration into the USML–1 Spacelab mission planned for March 1992. Thermocapillary flows are generated by a thermally induced surface tension variation which acts as a surface tractive force along a liquid/gas free surface from regions of low surface tension (high temperature) to high surface tension (low temperature).

During the STDCE a 10 cm diameter by 5 cm deep cylindrical container of silicone oil is heated centrally either, internally or externally, while the resulting thermocapillary flows are visualized by illuminating a cross section with a sheet of light. The internal heating case uses a 1.1 cm diameter by 5 cm height resistance heater (heated wall) placed centrally in the test cell (cooled wall) to establish the temperature gradient along the free surface. For the externally heated case, the resistance heater is removed and the free surface is heated by focused CO_2 laser radiation.

Because liquid/gas free surfaces are ubiquitous to containerless processes, the understanding of surface tension driven flows in reduced gravity as well as in terrestrial gravity is important in the commercialization of containerless materials processing techniques.[1] The surface temperature distribution is a critical parameter for these types of flows as it is the driving force.[2–3] In reduced gravity, a liquid/gas free surface may not be stationary due to small accelerations, called g–jitter, aboard the vehicle. Consequently, when the thermal boundary layer along the free surface is thin, contact surface temperature measurement methods are sensitive to these disturbances. Therefore development of a non–contact temperature measurement system to quantitatively characterize the thermal signature is an essential part of the development of the STDCE.

The system development has been divided into three phases: feasibility testing, contract development, and flight hardware design and construction. The feasibility testing phase was based on the science objectives put forth by the Principal Investigator, S. Ostrach and the Co–Investigator, Y. Kamotani, both of Case Western Reserve University, in the STDCE Science Requirements Document.[4] An absorption study of silicone oil was conducted to determine the most appropriate operating wavelength for the imager and the surface layer thickness measured by the imager. Based on the study results, a Model 600 Infrared Imaging System was purchased from Inframetrics, Inc. Testing was conducted using this system to determine its accuracy compared to thermocouple measurements and numerical calculations as well as an effective emissivity under these experimental conditions[5].

The contract development phase, consisted of combining technical specifications, environmental testing specifications, and a statement of work into a request for proposals. This process, along with the major specifications and their rationale can be found in detail in reference 6. Briefly, the technical specifications were based on the performance of the Inframetrics equipment, with several major modifications, while the testing specifications arose from Shuttle environmental conditions and safety considerations. The requirements include related development work, design reviews, vibration levels, safety and qualification/acceptance testing which must be met within the constrained schedule associated with the USML–1 Spacelab mission deadlines. The result of this procurement is a fully tested and Spacelab qualified infrared imager which can be integrated with the balance of the STDCE hardware.

The objectives of the present paper are to describe the third phase: the flight hardware design and development plan and an update of the major highlights of the ensuing contract[7] activities of the selected vendor. In addition to this specific application, possible opportunities for use of this instrument (with or without minor modifications) in conjunction with other Spacelab microgravity science experiments is mentioned.

2. PROPOSED INSTRUMENT

2.1 Development plan

As a result of the proposal evaluations, Barnes Engineering Division (BED) of EDO Corporation was selected as the prime contractor, along with Inframetrics, Inc. (IFX) as the sub–contractor, to supply NASA with a Spacelab qualified infrared imager based on the Inframetrics Model 600, including a LORIS scanner mechanism and modified Model 600 electronics. Per the NASA/BED and subsequent BED/IFX contracts, IFX supplies scanner mechanisms, detector/cooler assemblies and electronics artwork to BED. BED provides the electronics (with technical support from IFX), enclosures, analyses and flight qualification testing.

Because the major driver of this contract is schedule (hardware delivery in 15 months), the technically conservative approach is to utilize existing technology and eliminate any uncertain development work. Also, since the feasibility work had been done using similar Inframetrics equipment, good technical traceability between phases of experiment development is expected. A secondary, but important, long term design goal is to keep the design of the instrument as general as possible so that other experimenters developing Spacelab experiments could use this design as an "off the shelf" instrument, eliminating the duplication of expensive one time development costs.

Contract milestones are:

03/06/89	Contract Award
07/06/89	50% Design Review
12/13/89	Final Design Review
08/01/90	Delivery of First Flight Unit
10/02/90	Delivery of Second Flight Unit

2.2 Major technical specifications

The commercial units employ electromechanical galvanometers to perform horizontal and vertical scanning (4 kHz and 60 Hz respectively) of the field of view, focusing the incident radiation onto a single element HgCdTe detector. The analog signal from the detector is processed, digitized, and reformatted to a standard TV format. The digitized image information is converted to quantitative temperature information, via calibration curves stored on ROM, and can be accessed in real time while the standard TV signal is recorded on video tape and can be quantified after the fact using a thermal image processor. A comparison of the major technical specifications of the flight unit and the commercial Inframetrics Model 600 is shown in Table 1.

Table 1. Major Technical Specifications		
specification	flight	commercial
scanning mechanism	LORIS	MODEL 600
spectral response	8–14 μ	8–14 μ
NETD	0.2 ^{0}C	0.2 ^{0}C
MRTD	0.1 ^{0}C	0.1 ^{0}C
detector cooling	closed cycle cryocooler	LN_2
FOV	15^0 V x 20^0 H	15^0 V x 20^0 H
IFOV	1.8 mr (50% response)	2 mr (50% response)
dynamic range	8–bit, 48 dB	7–bit, 42 dB
frame rate	30 Hz (2:1 interlace)	30 Hz (2:1 interlace)
output format	RS–170A video	RS–170 video
filters	blocking: 10.50 ± 0.05 μ	selectable
focus	20.6"(9" front to target)	adjustable
measurement ranges	5,10,20,50,100,200 ^{0}C movable between 0 and 400 ^{0}C both man/auto select	5,10,20,50,100,200 ^{0}C movable between –20 and 400 ^{0}C + x–rng
Post flight		
Image analysis	Thermoteknix system ver. 3.0	Thermoteknix system ver. 2.0
size		
controller	6.2"D x 12.4"W x 11.2"H	8.1"D x 4.8"W x 4.9"H
scanner head	8.3"D x 5.4"W x 7.2"H	9.3"D x 10.3"W x 5.4"H
weight		
sensor head	7.7 lbs	6.5 lbs
electronics	17.3 lbs	7.5 lbs
power consumption	34 watts	10 watts
input voltage	12 VDC	11–17 VDC
non–operational shelf life	2 years	NA

2.3 Modifications

As shown in Table 1., several major modifications have been made to the scanner head. Some changes are necessitated by the environment during launch and orbit while others are experiment specific. Because of the vibration experienced on liftoff, the more rugged LORIS (military) scanner mechanism is utilized in lieu of the standard model 600 galvanometers. The LN_2 dewar is replaced by Inframetrics microcooler: a small, low power Stirling cycle cooler. The 7–bit analog to digital conversion in the commercial unit is replaced with an 8–bit converter to increase the dynamic range of the instrument. Where possible, the electronic components on each circuit board are replaced by Mil–STD electronics components. This change requires artwork modifications in three of the five PCB's to incorporate the larger Mil–STD components. For components where there is no Mil–STD, equivalent high quality parts are selected after proper derating and screening. The method of mounting the PCB's is also changed to facilitate heat dissipation and vibration tolerance. Because the power consumption is low no active cooling is required. The external structures are pressurized and sealed to contain any toxic gases which emanate from materials within the enclosures. The external dimensions are determined by the available space in the STDCE experiment package.

The STDCE is predominantly an automated experiment run by the STDCE experiment computer. Because complete automatic operation of the imager is not possible with the commercial unit, some development is needed to perform this task. This problem is solved by the addition of an auto-ranging microprocessor (ARMP) contained in the imager controller enclosure which acquires data from the imager and determines whether the most appropriate temperature range is selected. Commands can then be sent to the imager to change the temperature range and center temperature, if needed. This scheme is implemented through the serial interface to the microprocessor control over which all imager operations are performed, via either the front panel (which is eliminated on the flight unit) or an external computer.

The ARMP acquires image intensity data through the "data dump" auxiliary mode. This mode outputs the intensity values across a selected line of the image, sending the information as 16 rows of 16 hexadecimal values through the serial interface. The ARMP determines the min and max values and commands the imager to adjust the temperature range and center temperature according to rules written in the software.

The number and location of the lines to be scanned are selectable during fabrication and are dependant on two factors. One, the speed at which the algorithm can adjust the imager settings and two, the allowable loss of data. The second factor arises because overlays, primarily on the line of pixels which is scanned, are placed on the image during use of the "data dump" auxiliary mode. This loss of data is minimized by switching back to the "data acquisition mode" after the data is sent to the ARMP. For each line scanned, the overlay remains on the image for several seconds. The first factor is a trade off between number of lines scanned and algorithm elapse time. Ideally, all pixels in the image should be considered before adjusting the imager settings, but this is prohibited by the approximately 20 minute acquisition time.

For this application, the locations of the min and max temperatures are well known so that several lines can be selected in these regions, reducing the acquisition time to approximately 10–15 seconds. Additionally, the ARMP acts as a buffer between the STDCE experiment computer and the imager. Commands are sent to the imager from the STDCE computer using full RS-232 protocol. The ARMP interprets these commands, determines whether the command is directed towards the ARMP or the imager, and, accordingly, accepts or passes it using the imager serial protocol.

Selectable spectral filters will not be available on the flight unit, as is possible with the commercial equipment. But, the spectral band pass of the flight unit is tailored by selectively coating windows in the optical path. For the STDCE, a 10.6±0.05 μm blocking coating is added to the exit window of the galvanometer housing. This coating prevents reflected CO_2 laser radiation from saturating the detector, if the silicone oil free surface deforms in such a way as to direct this radiation into the imager. To compensate for the loss of throughput, or lower NETD (noise equivalent temperature difference), caused by the addition of the blocking filter, the focusing lens diameter is changed from 0.57" to 0.647".

Block diagrams of the flight scanner head and controller are shown in Figure 1.

3. PROTOTYPE PERFORMANCE

A prototype imager or engineering test unit (ETU) was constructed by Inframetrics using the LORIS scanning mechanism, microcooler, and modified model 600 electronics as a proof of concept. The ETU scanner head is shown in Figure 2. Several different detector/cooler combinations were tried in the ETU depending on the currently available hardware. In this way, different aspects of the new unit, such as the integration of the microcooler and additional drive circuitry, and preliminary detector characteristics, could be tested immediately without the delays associated with the assembly of a complete system. The first configuration tested utilized a non-optimal detector coupled with the microcooler and associated hardware to check the functionality of the design. In the second configuration, a NETD optimized detector, but with a broad band coating (3–12 μm), coupled with a LN_2 dewar was installed into the ETU to test the NETD and IFOV (instantaneous field of view). The resulting NETD and IFOV obtained with this configuration were 0.09 degrees C and 45% at 2.0 mRad. Based on these results, the projected NETD and IFOV of the flight model are 0.14±0.02 degrees C and 50% at 1.8 mRad. Data taken from the ground-based STDCE hardware (heating with the CO_2 laser) using the commercial Inframetrics model 600 are shown in Figures 3 and 4. These data are representative of the character and accuracy expected from the flight imager.

Because little formal data has been gathered in the past, preliminary vibration tests were conducted on key components of the imager, namely the microcooler and galvanometers, in order to diagnose and correct any problems before the final design is completed. The vibration levels these components must withstand is approximately 15 g RMS. Both the vertical and horizontal galvanometers withstood the test without any misalignment. The microcooler suffered only a broken solder connection, with no damage to the compressor bearings. Tests are also being conducted on the microcooler to determine, formally for a small control sample (2 units), the operational lifetime of the microcooler. A lowered fill pressure is expected to add to this lifetime. The goal for the STDCE is to achieve a lifetime greater than 500 hours.

4. CONCLUDING REMARKS

The USML–1 Spacelab mission is the first in a series of four Shuttle flights dedicated to performing US science experiments. With these experiments the need for qualitative and quantitative thermal imaging will become greater. These experiments include fluid physics problems, such as levitated drops, both high and low temperature, other surface tension driven flows and combustion experiments, both solid and gas phase. Experimenters are beginning to use this technology as qualitative and quantitative diagnostic tools in terrestrial laboratories. Simultaneously, flight experiment developers will be searching for ways to incorporate this technology into cost effective experiment modules which maximize the quality and quantity of the flight data. The philosophy behind the present development is to eliminate many of the one time costs associated with flight qualification of sophisticated terrestrial hardware. The design of the STDCE imager has the ability to be changed to suit other experiments with little impact on the expensive and time consuming one time tasks, such as design and analyses. For instance the spectral characteristics of the imager can be tailored to suit the particular experiment: 3–5 μm for combustion and high temperature materials experiments and 8–14 μm for low temperature materials and fluids experiments or any band pass between 3–14 μm depending on the spectral characteristics of the target. As with the STDCE, spectral filters can be added by coating existing optics in the optical train. The temperature range of the imager can also be changed to include an extended range (offered commercially) for higher temperature experiments. Both of these changes can be incorporated without changing the basic design of the imager. One time costs such as structural and thermal analyses, selection of Mil–STD parts, and prototype development need not be repeated to flight qualify a new instrument of (virtually) the same design.

ACKNOWLEDGEMENTS

The authors would like to thank the members of the STDCE design team for their efforts with the Barnes and Inframetrics teams during design of the flight imager. This interaction was invaluable to insure that the imager design was compatible with and optimized for the STDCE hardware.

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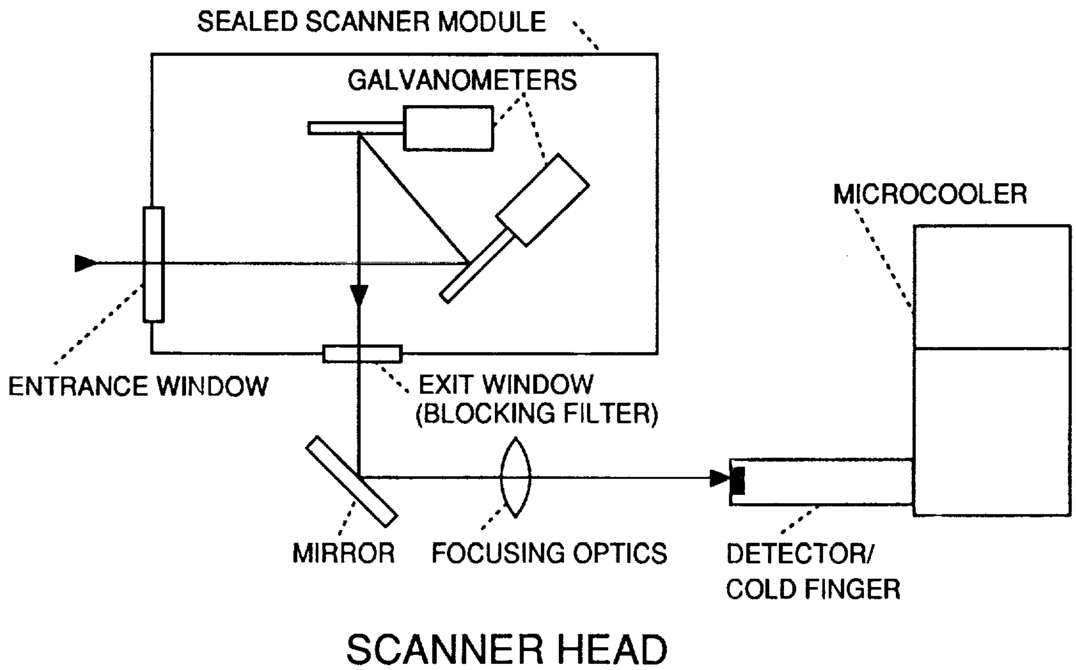

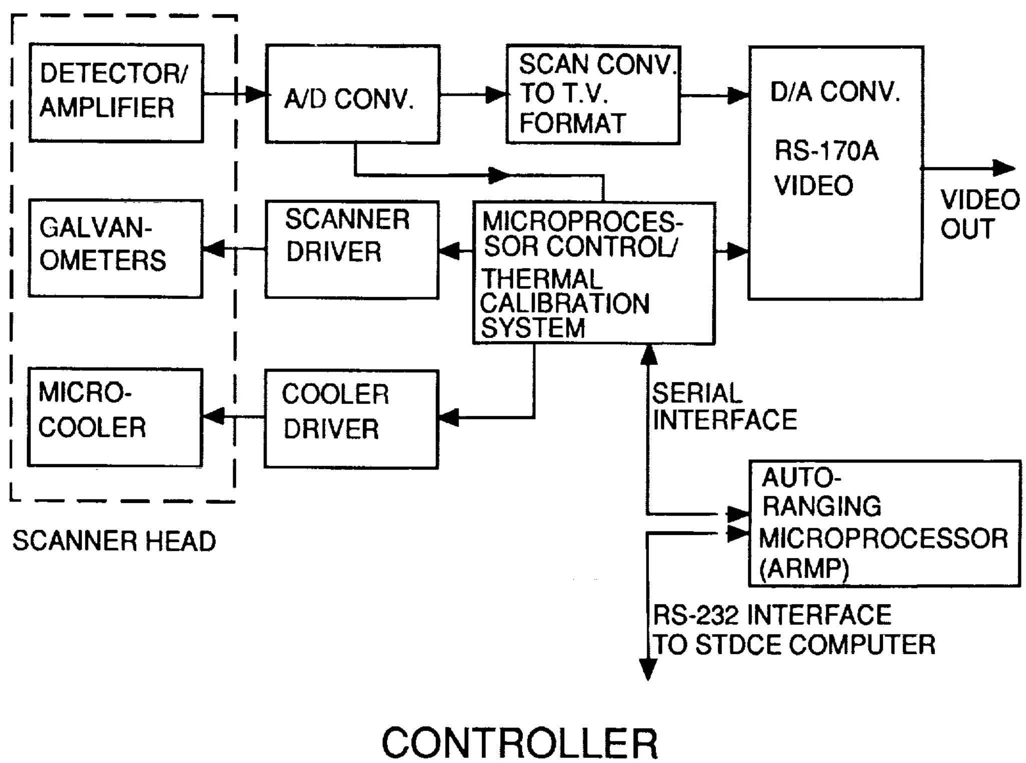

Figure 1. Flight IR imager block diagrams.

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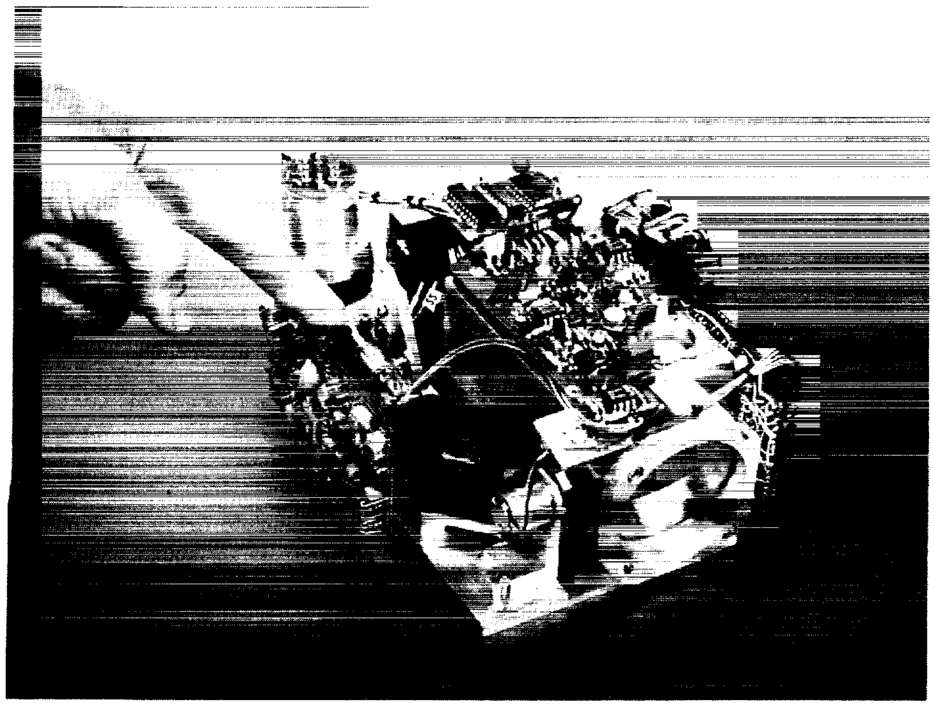

Figure 2. ETU scanner head.

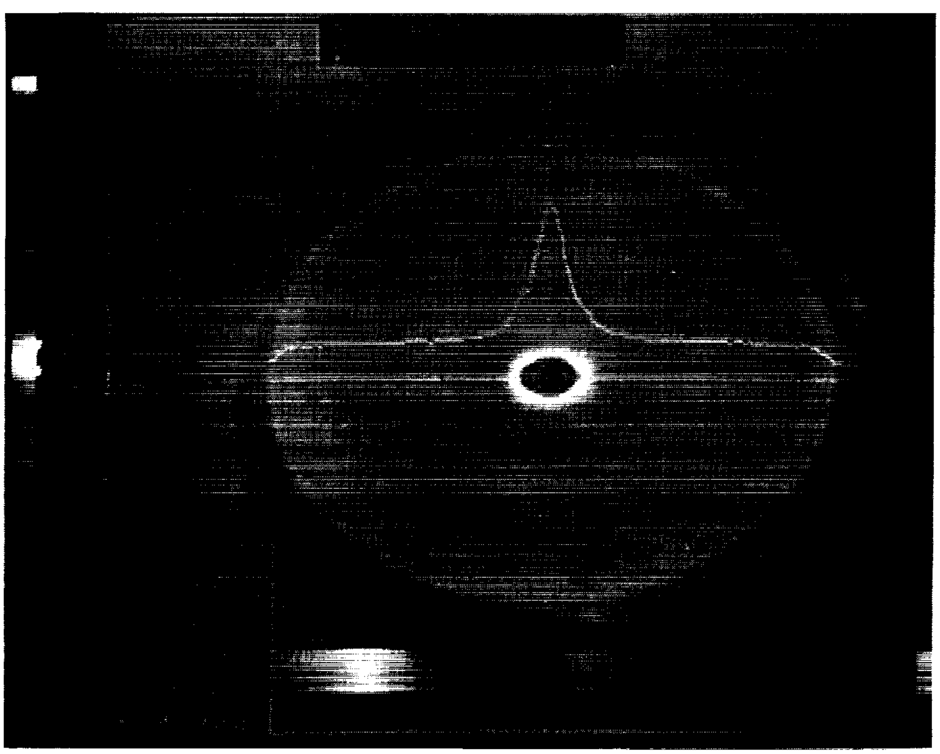

Figure 3. Thermogram of the STDCE with external (CO_2 laser) heating driving the thermocapillary flow.

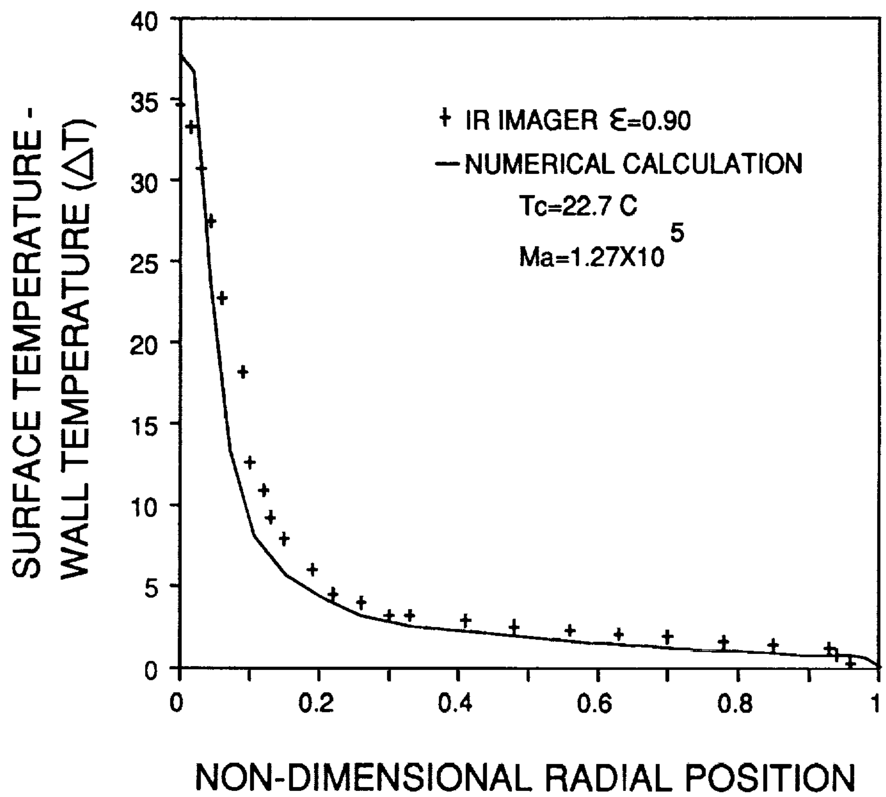

Figure 4. Resulting surface temperature distribution from a thermogram, similar to that shown in Figure 3, compared with a numerical prediction.

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Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA TM-102503		

4. Title and Subtitle	5. Report Date
Spacelab Qualified Infrared Imager for Microgravity Science Experiments	
	6. Performing Organization Code
7. Author(s)	8. Performing Organization Report No.
Alexander D. Pline and Robert L. Butcher	E-5304
	10. Work Unit No.
	694-03-03
9. Performing Organization Name and Address	11. Contract or Grant No.
National Aeronautics and Space Administration Lewis Research Center Cleveland, Ohio 44135-3191	
	13. Type of Report and Period Covered
12. Sponsoring Agency Name and Address	Technical Memorandum
National Aeronautics and Space Administration Washington, D.C. 20546-0001	14. Sponsoring Agency Code

15. Supplementary Notes

Prepared for the Technical Symposium on Optical Engineering and Photonics in Aerospace Sensing, sponsored by the Society of Photo-Optical Instrumentation Engineers, Orlando, Florida, April 16-20, 1990.

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17. Key Words (Suggested by Author(s))	18. Distribution Statement
Infrared imaging Microgravity Surface tension driven convection experiment	Unclassified – Unlimited Subject Category 35

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of pages	22. Price*
Unclassified	Unclassified	10	A02

NASA FORM 1626 OCT 86

*For sale by the National Technical Information Service, Springfield, Virginia 22161